Nuclear physics with a medium–energy EIC
C. Weiss (JLab), POETIC Workshop, Indiana University, Bloomington, 20–Aug–12

- Overview of $ep/eA$ physics with “generic” medium–energy EIC

  $\sqrt{s} = 20–70$ GeV, $L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$


- Guiding principles

  Focus on physical system, not formal descriptors:
  “What do we learn about dynamics?”

  Unifying perspective low $\leftrightarrow$ high energies

I) 3D structure of nucleon in QCD
   - Sea quark and gluon polarization
   - Spatial distributions, orbital motion
   - Multiparton correlations

II) Fundamental color fields in nuclei
   - Nuclear quark/gluon densities
   - Shadowing, coherent processes
   - Color transparency

III) Emergence of hadrons from color charge
   - Color neutralization, hadron formation
   - Interaction of color charge with matter
3D nucleon structure: Fields and particles

- Hadrons in QCD
  Relativity: Particle creation/annihilation, space–time picture frame dependent
  Strong interactions: Vacuum structure, non–perturbative effects
  Quantum mechanics: Fluctuations
  Uniquely challenging dynamical system!

- Field–theoretical description
  Imaginary time $t \rightarrow i\tau$, statistical mechanics
  Lattice QCD; analytic methods

- Particle–based description
  Parton picture $P \rightarrow \infty$: Wave function
  Feynman, Gribov: Closed system. Alt: Light–front quantization
  Components with different particle number
  Many–body system: Constituents, interactions, spatial structure, orbital motion, . . .
  High–energy process takes snapshot
  Short–distance interactions: Factorization
3D nucleon structure: Landscape

- **Components probed** predominantly
  
  - $x > 0.1$ Valence quarks: Source, quantum numbers  
    Also gluons at large $x$!  
    Intrinsic sea $s\bar{s}, c\bar{c}$?
  
  - $x \sim 10^{-1}$ Sea quarks, gluons:  
    Quantum numbers  
    Generated by non-perturbative QCD interactions!
  
  - $x < 10^{-2}$ Gluons, singlet sea:  
    Radiatively generated  
    Saturation at small $x$: New dyn. scale  
    Learn about interactions!

- **Quantities measured**
  
  Particle number densities, incl. spin/flavor dependence  
  PDFs
  
  Transverse spatial distributions  
  GPDs
  
  Orbital motion, angul. momentum  
  TMDs
  
  Particle correlations  
  MP distributions, GPDs
  
  Densities with operator definition $\langle N | \text{QCD–Op} | N \rangle$  
  Calculable with non-perturbative methods  
  Scale dependence from RNG equation.
3D nucleon structure: Sea quark polarization

• How are sea quarks polarized in nucleon?

  Non-perturbative QCD interactions connecting valence $\leftrightarrow$ sea quarks

  Role of mesonic degrees of freedom?

• Semi–inclusive scattering: Identify particles produced from struck quark

  Flavor asymmetries poorly constrained by present data
  HERMES SIDIS
  First constraints from RHIC $W$ data

• EIC: Map sea quark distributions and their spin dependence

  High energy ensures independent fragmentation of struck quark
3D nucleon structure: Gluon polarization

- What is the polarized gluon distribution?
  Origin of non-perturbative gluon fields?
  "Constituent quark" structure, quark correlations?

- ∆G(x) presently poorly constrained
  Q^2 dependence of g1(x, Q^2)
  EMC/SMC, SLAC, HERMES, COMPASS, JLab 6/12 GeV

- EIC: Fully quantitative determination
  Good results already with medium energy → Talk Stratmann

- Quark/gluon orbital angular momentum
  Much progress in theoretical understanding
  INT Workshop Feb–12; many recent papers

  Manifest in semi–inclusive spin asymmetries
e.g. Sivers effect → Talk Prokudin

  Challenge to separate OAM in wave function
  from QCD final–state interactions
  → Talk Burkardt

M. Stratmann, INT Workshop 2010
3D nucleon structure: Spatial distributions

- How are quarks/gluons distributed in transverse space?
  - Fundamental size and “shape” of nucleon in QCD
  - Distributions change with $x$:
    - Diffusion, chiral dynamics
  - Input for saturation models, multiparton interactions in $pp@LHC$

- Exclusive processes $\gamma^* + N \rightarrow J/\psi + N$
  - Gluonic form factor of nucleon:
    - Generalized parton distribution
  - Other channels $\gamma, \rho^0, \pi, K$ sensitive to quarks → Talks Hasch, Liuti, Fazio

- EIC: “Gluon imaging” of nucleon
  - Luminosity for low rates, differential measurements
Color fields in nuclei: Physics

- What are the fundamental color fields in nuclei?
  
  Modification of nucleon structure

  Collective effects $A \neq \sum N$

  Non–nucleonic degrees of freedom

  → QCD origin of $NN$ interaction at different energies
  → Approach to black–disk/saturation regime

- Interaction with high–energy probe

  Transverse resolution $r \sim 1/Q$

  Coherence length $l_{coh} \sim \nu/Q^2 \times \text{factor}$

  Final states: Inclusive, identified spectators, exclusive, . . .
Color fields in nuclei: Landscape

- Fields probed in $eA$
  
  $l_{coh} \ll R_A$: Modified nucleon structure, short–range correlations
  
  JLab 12 GeV: EMC effect for valence quarks
  EMC effect for gluons, antiquarks?

  $l_{coh} \gg R_A$: Collective effects
  
  New regime accessible with medium–energy EIC!

- QCD phenomena

  Shadowing: QM interference in scattering from multiple nucleons
  Is it different for gluon and quark fields?

  Color transparency: Disappearance of interaction for small probes $\sigma \propto r^2$
  
  Fundamental prediction of QCD as gauge theory

  Coherent scattering: Quark/gluon fields of entire nucleus Nuclear GPDs, quark/gluon size

  Quantum fluctuations: Diffraction

  Saturation: Strong gluon fields, black disk regime in hard interactions
  
  New dynamical scale $Q_s$
Color fields in nuclei: Gluon density

- Nuclear quark/gluon densities
  \( x > 0.1 \) “EMC effect”: Modification of free nucleon structure:
  \( x \sim 0.1 \) Antishadowing: Poorly understood
  \( x \ll 0.1 \) “Shadowing”: QM interference

- Gluon poorly constrained
  \( Q^2 \) dependence of nuclear structure function \( F_{2A}(x, Q^2) \)

- Medium–energy EIC: Precise determination of nuclear quark/gluon densities
  Wide coverage in \( x, Q^2 \)

- Important for understanding approach to saturation at small \( x \)
  Shadowing affects nuclear enhancement of \( Q_s \)
Color fields in nuclei: New probes with EIC

- **Spectator tagging**
  
  Bound nucleon structure: EMC effect

  Neutron structure from $D(e, e^{'p})X$

  JLab BONUS experiment

  Requires forward $p/n$ detection

- **Coherent nuclear processes** $A(e, e^{'M})A$

  Fundamental quark/gluon radii of light nuclei

  Kowalski, Caldwell 09: Heavy nuclei, very challeging

  Impact parameter dependent shadowing

- **Color transparency in meson production**

  Fundamental prediction of QCD

  Complement to saturation experiments: “Disappearance” at high $Q^2$
Hadrons from color charge: Fragmentation

• How do hadrons emerge from QCD color charge?

Conversion energy → matter
Cosmic ray physics, early universe

Dynamical mechanisms: QCD radiation, pair creation by soft fields
Vacuum structure, $q\bar{q}$ condensate

• Fragmentation functions from $e^+e^-$

Many puzzles: $s\bar{s}$, kaons, baryons
Essential input to SIDIS

• EIC: New possibilities

Fragmentation functions from $ep$:
Favored ↔ unfavored, test universality

Target fragmentation: How does nucleon with “color hole” materialize?
$x$, spin dependence

Correlations current–target regions:
Multiparton correlations
New field of study: $pp$ at LHC
New possibilities for nucleon structure

Qualitatively new! Many applications! Unique for EIC
**Hadrons from color charge: Matter**

- How does fast color charge interact with hadronic matter?
  
  Energy loss, attenuation
  
  Time scales for color neutralization $t_N$, hadron formation $t_F$
  
  Cold vs. hot matter? $eA/\gamma A \leftrightarrow$ jets in $AA$

- EIC: Comprehensive studies
  
  Wide range of energy $\nu = 10 - 100$ GeV:
  Move hadronization inside/outside nucleus, distinguish energy loss and attenuation
  
  Fixed-target: Correlations $\nu-Q^2$
  
  Wide range of $Q^2$: QCD evolution of fragmentation functions and medium effects
  
  Hadronization of charm, bottom: Clean probes, QCD predictions
  
  High luminosity: Multidimensional binning
  
  $\sqrt{s} > 30$ GeV: Study jets and their substructure in $eA$

[Graphs and diagrams are not transcribed here.]
Summary

- Unique nuclear physics program with medium-energy EIC $\sqrt{s} = 20-70$ GeV
  
  Three-dimensional structure of nucleon in QCD  
  Fundamental color fields in nuclei  
  Emergence of hadrons from color charge

  *Natural organization . . . could be sharpened further!*

- Focus on what we learn about the dynamical system

  Many questions addressed by more than one measurement: 
  Orbital angular momentum — inclusive $\Delta G$, semi-inclusive asymmetries; 
  Quark correlations — exclusive and semi-inclusive processes

- Qualitatively new probes available in $eA$

  Spectator tagging, coherent processes: Should be developed further!
  
  $ep$ better formalized, but $eA$ completely new